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Original Research

Theoretical Analysis of the Effect of Temperature on Current Delivery to the Brain During tDCS

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ABSTRACT

Background: Transcranial direct current simulation (tDCS) is a non-invasive neuromodulation technique that has become increasingly popular as a potential therapeutic method for a variety of brain disorders. Since the treatment outcome may depend on the current density delivered to the brain cortical region, a significant challenge is to control the current dose reaching the cortical region.

Objective and methods: This study aims to investigate the effect of temperature on current delivery to the brain. We devised a method for modulating the amount of current delivered to the brain by changing the temperature of the scalp. We developed analytical and numerical models that describe the relationship between temperature and electrical properties of the scalp based on the following mechanisms: ion mobility and blood perfusion in scalp.

Results and conclusions: The current delivery to brain was investigated by changing the temperature between two electrodes that are attached to the surface of the scalp, within a tolerable physiological range. Results show that by increasing the temperature between two electrodes, a higher portion of current is shunted via the scalp and the proportion of the current that penetrates the scalp and skull into brain is decreased. On the other hand, cooling the area between two electrodes on the scalp increases the current delivery to the cortical region of the brain. Our results show that cooling the scalp during tDCS can be considered as a possible way to effectively control the current delivery to the brain and increase the efficacy of tDCS.

Introduction

Transcranial Direct Current Stimulation (tDCS) is a non-invasive neuromodulation technique that has shown a promise for the treatment of a wide variety of neurological disorders [1]. tDCS consists of applying a weak direct electrical current (1–2 mA) to the brain through non-invasive surface electrodes placed on the scalp of a subject. While interest in applying tDCS for treating of different neurological conditions has been growing, there are still several concerns regarding its practical applications which need to be addressed [2,3]. One of the main challenges is to control the current dose reaching the cortical region. Depending on the size and position of the electrodes, a significant proportion of the stimulation current is shunted from the anode to the cathode via the scalp, due to the high resistivity of the skull [4], thus reducing the proportion of the total current that reaches the cortex. Since treatment efficacy is correlated to intra-cranial current density, reduction of current shunting may improve treatment outcome [5,6]. Delivery of a higher percentage of the applied current to the brain is desirable as it allows limiting the injected current to 2 mA or less, hence mitigating the safety concerns associated to skin lesion or irritation [7,8].

The electrical properties of the tissue can be altered by changes in temperature related processes such as ion mobility, blood perfusion and skin water permeability [9–11]. A commonly cited model approximates the changes in tissue conductivity resulting from temperature modulation as a function of the thermal coefficient of ion mobility [12]. The model states that for temperature changes within a defined physiological range, a linear approximation can be used to show the relationship between tissue conductivity and temperature. A general tissue conductivity increase occurs since the mobility of the ions that transport the current increases with the temperature as the viscosity of the extracellular fluid decreases [13].

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The scalp conductivity depends on several factors such as head shape, scalp thickness, anisotropy coefficient, blood perfusion, and so on. In addition, temperature is shown to have a significant effect on conductivity of the scalp [14]. According to the reports, increasing the scalp temperature (within physiologically tolerable temperature changes) may double scalp conductivity. Blood perfusion is another important physiological mechanism responsible for temperature dependence of scalp electrical properties. Blood perfusion has a direct effect on tissue conductivity since blood is much more conductive than other body tissues [15]. Blood flow to the scalp tissues is increased by elevating the tissue temperature resulting in an increase in electrical conductivity. Changes in blood perfusion due to the temperature variation are modeled based on an empirically derived equation that relates variation in tissue temperature to corresponding changes in cell metabolism and tissue blood perfusion [16]. The interplay between tissue temperature and blood perfusion has been investigated in several researches by cooling the scalp as a possible solution to hair preservation during the chemotherapy treatment [17].

In this paper, we introduce a new method for the enhancement of current delivery into the brain during tDCS. The method is based on the temperature dependence of electrical properties of scalp tissue which to the best of our knowledge, has not been investigated in previous studies. Electrical conductivity of the scalp can be regulated by changing the temperature. The proportion of stimulation current reaching the intra-cranial region (dose) can be controlled. We considered the effect of ion mobility and blood perfusion in order to develop a mathematical expression between electrical conductivity of the scalp and temperature. Water permeability through skin is not considered since the effect is negligible for the temperature range examined in the present study [18]. We developed an analytical model of current delivery through a simplified 3 layer segment of scalp, skull and brain that describes how temperature affects intra-cranial current density. In order to account for the effect of the temperature gradient variations through the tissue we also implemented a finite element model (FEM) model that takes into account bio-heat phenomena.

Theory and methods

In this section we develop a mathematical model that describes the relationship between the temperature and electrical conductivity of the scalp. The specific conductivity of scalp is evaluated using thermal coefficient of ion mobility and blood perfusion in tissue. In the sub GHz frequency range up to a temperature of about 40 °C, a linear relation can be used to describe the effect of the temperature on the electrical conductivity of the tissue due to ion mobility using a temperature coefficient of about 2% per degree [14]. Assuming that the baseline temperature of body tissue is T_0 and current temperature is T; the variation in the specific conductivity of the tissue with temperature due to ion mobility can then be given by:

$$\sigma(T) = \sigma_0 \times (1 + 0.02 \times (T - T_0)) \quad (1)$$

where σ_0 is the tissue specific conductivity at T_0 and temperature is in °C.

The scalp consists of several components such as muscle, fat, epidermis, dermis and blood. The conductivity of blood is much higher than the other components [14,15]. We will take into account two main components in our simplified scalp model: the highly conductive component of blood with relative temperature dependent weight of $\omega_b(T)$ where $\omega_b(T)$ is the temperature dependent coefficient of scalp conductivity due to blood perfusion, and less conductive component of the constant weight x_r that is related to the remaining components such as muscle, fat and so on [14]. Based on this model, the relation between average specific conductivity of the scalp with temperature can be given by:

$$\sigma_{scalp}(T) = \omega_b(T) \times \sigma_b(T) + x_r \times \sigma_r(T) \quad (2)$$

Using Eq. (1), the temperature dependency of the conductivity of blood $\sigma_b(T)$ due to ion mobility can be given as,

$$\sigma_b(T) = \sigma_b(T_0) \times (1 + 0.02 \times (T - T_0)) \quad (3)$$

where $\sigma_b(T_0)$ represents the conductivity of blood at baseline scalp temperature T_0 and $\sigma_r(T)$ can also be given from Eq. (1) as

$$\sigma_r(T) = \sigma_r(T_0) \times (1 + 0.02 \times (T - T_0)) \quad (4)$$

where σ_r is the average conductivity of the remaining tissues in the scalp without blood and T_0 shows the baseline temperature of the scalp.

From Eqs. (2–4), the scalp conductivity variation with temperature can be obtained as

$$\sigma_{scalp}(T) = [\omega_b(T) \times \sigma_b(T_0) + x_r \times \sigma_r(T_0)] \times (1 + 0.02 \times (T - T_0)) \quad (5)$$

Blood perfusion in scalp is very sensitive to temperature. The relation between blood perfusion and temperature is modeled according to Q_{10} equation, an empirically derived relation of thermal physiology which states that for each 10 °C change in temperature, there is a corresponding variation in blood perfusion with constant coefficient Q_{10}, thereby:

$$\omega_b(T) = \omega_b(T_0) \times Q^{\frac{T-T_0}{10}} \quad (6)$$

where the reported value of parameter Q_{10} is between 2 and 3 [9].

Analytical model

The electrical properties of the head are described by a 3-layer model which includes scalp, skull and the brain. Note that the brain component is composed of gray matter, white matter and CSF. Two round current electrodes E_1 and E_2 of radius r are attached to the surface of the scalp layer separated by distance L. Figure 1 shows the developed model and current propagation via the surface electrodes (only scalp and skull layers are shown). The corresponding circuit model is shown in Fig. 2. We will neglect the nonlinear effects associated with charge movement and redistribution during tDCS [19]. When delivering a DC current into the scalp, the total resistance between the electrodes is given by:

$$Z_t = \frac{Z_1 \times Z_2}{Z_1 + Z_2} \quad (7)$$

where Z_1 is the scalp resistance; $Z_1 = Z_{scalp}$, and Z_2 represents the resistance of the skull and brain in series. Since the brain resistance is much less than the skull resistance [20–22], the amount of resistance Z_2 can be approximated by the skull resistance,

$$Z_2 = Z_{skull} + Z_{brain} \simeq Z_{skull} = 2 \times Z'_{skull} \quad (8)$$

By considering the scalp as an isotropic conductive layer of thickness d_{scalp} and specific resistivity ρ_{scalp}, a simple estimate of maximum scalp resistance can be directly obtained by the following equation:

$$Z_{scalp} = \frac{\rho_{scalp} \times L}{2 \times r \times d_{scalp}} \quad (9)$$